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Discussion

Paris Climate Agreement: Promoting Interdisciplinary Science and Stakeholders' Approaches for Multi-Scale Implementation of Continental Carbon Sequestration

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Abstract: The Paris Climate Agreements and Sustainable Development Goals, signed by 197 countries, present agendas and address key issues for implementing multi-scale responses for sustainable development under climate change—an effort that must involve local, regional, national, and supra-national stakeholders. In that regard, Continental Carbon Sequestration (CoCS) and conservation of carbon sinks are recognized increasingly as having potentially important roles in mitigating climate change and adapting to it. Making that potential a reality will require indicators of success for various stakeholders from multidisciplinary backgrounds, plus promotion of long-term implementation of strategic action towards civil society (e.g., law and policy makers, economists, and farmers). To help meet those challenges, this discussion paper summarizes the state of the art and uncertainties regarding CoCS, taking an interdisciplinary, holistic approach toward understanding these complex issues. The first part of the paper discusses the carbon cycle's bio-geophysical processes, while the second introduces the plurality of geographical scales to be addressed when dealing with landscape management for CoCS. The third part addresses systemic viability, vulnerability, and resilience in CoCS practices, before concluding with the need to develop inter-disciplinarity in sustainable science, participative research, and the societal implications of sustainable CoCS actions.

Keywords: climate change and sustainable development; continental carbon sequestration; multi-scalar management; carbon modelling; participative research

1. Introduction

The Paris Agreement (Drafted at the 21st Conference of the Parties of the United Nations Framework Convention on Climate Change (UNFCCC)) aims for preventing the global average temperature from exceeding pre-industrial levels by more than 2 °C before the year 2100. It emphasized that an increase of only 1.5 °C would probably exacerbate natural hazards. The Agreement's targets will not be met if greenhouse gas (GHG) emissions are not reduced. Therefore, the world must shift—urgently—to a socio-environmental paradigm with lower or even negative GHG emissions [1].

Negative GHG emissions can be achieved by three main processes: natural processes, chemical transformation—or mineral carbonation—and engineering technics. Although progress has been made on Carbon Capture and Storage technology (CCS) to capture more than 80 to 90% of carbon dioxide (CO_2) generated from power plants, challenges to assess and reduce environmental risks and high costs remain. Those risks and costs involve capturing, transporting and storing CO_2 into geological formations and water bodies bottoms [2–4]. Chemical transformations include uses of industrial wastes or crushed rocks to capture and store CO_2 into carbonates [5–7]. Using crushed rocks mimics and enhances the natural weathering process. During weathering, silicates rocks release CaO and MgO minerals which react with CO_2 to form carbonates. These processes are thus enhanced by crushed rock amendment containing calcium and magnesium on crop or forest soils [5–7]. These amendments favour carbon sequestration potential at affordable costs and could have positive co-benefits (e.g., P availability), especially in acid soils [3]. Even if these technics seem safe and affordable, research are still needed to assess their benefits and externalities taking into account all of the system, including logistics and transports of the crushed rocks to the soils [4].

Compared to these engineering techniques, continental C sequestration based on the natural process of photosynthesis, i.e., based on C storing into terrestrial and aquatic ecosystems, e.g., into biomass, soils, and sediments are more cost effective, provides co-benefits—e.g., ecosystem services—and are easier to implement on vast scale [7,8]. Furthermore, Carbon Capture and Storage Technologies (CCS) and Bioenergy Combined with Carbon Capture and Storage (BECCS) present higher costs (around US$ 15–400 tCO2eq.−1, [9]) compared to costs related to agricultural climate policy implementation (~US$ 4–23 tCO2eq.-1 [10]). As a consequence, agriculture and landscape management, using carbon sink potentials, offer promising options to mitigate GHG emissions and moving towards negative emissions.

Our discussion paper focuses on these natural processes based on photosynthesis. Those involve the vegetal cover, its management, as well as the biotic and soil carbon pool, i.e., the organic carbon pool localized in biomass, on the soil and sediment surface layer (0–1 m). Preserving and enhancing these natural CO_2 capture in continental ecosystems (According to [11] (p. 1452), an ecosystem is "a functional unit consisting of living organisms, their non-living environment and the interactions within and between them") need to be documented (quantification of the amount of GHG saved, context specificities, co-benefits and risks, implementation and long-term preservation policies) and developed at several levels.

That paradigm requires a strong involvement of societies and stakeholders in ecosystems—e.g., socio-ecosystems (A short list of socio-ecosystems includes socio-ecological systems and coupled human-nature systems. Publications about socio-ecosystems describe relationships between humans and non-humans insightfully, and aim to reconnect humankind with the biosphere and ecological systems [12]. Reference [13] describes coupled human-nature systems briefly as "integrated systems in which people interact with natural components". [14] based its reflection upon the concept of "common resource(s)" and how to govern them. Four subsystems are identified: the ecological system, the economic system, the politic system, and the socio-anthropological system.)—to mitigate and adapt to the current climate change. Identifying and implementing measures for transitioning to socio-ecosystems is a multi-level task [2,3], facilitated by finding ways to reduce GHG emissions while increasing C storing. Such developments and measures must be viable, sustainable and equitable.

According to [7], "sequestering C involves transfer of atmospheric CO_2 into other pools where it is securely stored and has a minimal chance of leakage back into the atmosphere". As seen above, several options of C sequestration are mentioned in the existent literature, and include geologic, oceanic, chemical, and terrestrial sequestration. We here focus on terrestrial and aquatic continental sequestration. At the ecosystem level, Continental Carbon Sequestration (CoCS) could be defined as the difference between the quantity of C captured and the C-CO_2 equivalent of all the GHGs emitted [15]. Greenhouse gases (GHGs) include CO_2, CH_4, and N_2O. All continental ecosystems—whether terrestrial or aquatic [16,17], natural, agricultural, or urban [18]—emit GHGs while also being C sinks [19]. In general, CoCS is a natural process that can be either impaired or enhanced by soil-, crop- and land-management practices, whatever the level of anthropization, on scales from individual plots to landscapes. In a first approximation, the simplest solutions proposed to enhance CoCS are the avoidance and limitation of deforestation [20], the promotion of agricultural systems with cover crops and/or trees and organic matter fertilization [21–23]. These solutions are mainly based on the enhancement of the organic carbon pool, which is a dynamic pool at the scale of years.

Increasing, and maintaining CoCS to avoid leakage, is thus a complex challenge because continental systems are intricate webs of interactions among the atmosphere, ground, water courses and water bodies, as well as with floristic, animal, and human communities. Nevertheless, understanding those systems is indispensable to finding ways of reducing GHG emissions and capturing C. Agriculture, Forestry and Other Land Use (AFOLU [11]) are recognized as a sector that plays a major role in that area [6,18].

Enhancing CoCS is particularly difficult when trying, at the same time, to meet the UN's Sustainable Development Goals (SDGs), particularly "Zero hunger" (Goal 2), "Climate action" (Goal 13), "Life on land" (Goal 15), "Responsible consumption and production" (Goal 12), and "No poverty" (Goal 1). The challenge becomes greater for countries that depend strongly upon exploitation of natural resources—particularly via agriculture [24]—or whose priorities are to meet their populations' needs for food, justice, social equity and security. The AFOLU sector is a crossroads where concepts of ecosystems, coupled human-natural systems, and their interactions are fundamentally questioned within the framework of CoCS.

We call for an interdisciplinary approach to CoCS as a thematic field, dedicated to transdisciplinary treatment of issues identified through strong commitment to stakeholders' involvement in development. Those issues include SDGs and local/regional effects of global climate change. In this article, authors from several fields (Earth sciences and Social sciences) examine the feasibility, scope, and durability of the various measures dedicated to develop natural carbon (C) storage and continental C sequestration (CoCS). The authors' interlaced considerations and observations providing essential backgrounds for promoting legal and operational tools to enhance CoCS. Pluri-disciplinary research is needed to tackle these issues related to several SDGs in various contexts and at different scales. This article is the result of a pluri-disciplinary discussion on CoCS. A strong structuration of the article in short paragraphs was chosen to allow each discipline to recognize their own research priorities and in while integrating other disciplines inputs. The first sections of this paper discuss quantification of C stocks and fluxes; current understandings of CoCS and its geochemical processes; and the challenges (e.g., knowledge gaps) of modelling CoCS across geographical and temporal scales. The physical scientists who wrote those sections also treat human practices—a field in which they have collaborated extensively with the social scientists who contributed subsequent sections on sustainable sciences and the co-construction of knowledge by non-academicians and main stakeholders. That co-construction can in some cases fill the natural scientists' "knowledge gaps". Perhaps even more importantly, co-construction of knowledge is crucial to promote CoCS as beneficial for economic, political, and socio-anthropologic systems. Therefore, the co-construction process may itself nourish inter- and intra-disciplinary questionings, and lead to recommendations.

Throughout the article, we will underline types of actionable knowledge that are most needed for researching CoCS productively and paths for its implementation.

2. Terrestrial and Aquatic C Pools: Processes, Uses, Management, and Budgets

2.1. C Pools and Fluxes

2.1.1. C Pools: Organic and Inorganic C in Natural Systems

Continental C pools include organic matter (OM) present in soils, waters, and biomass, plus inorganic C compounds (CO_2, dissolved inorganic C (DIC) and carbonates) found in soils, waters, and the air. These pools hold 2000 to 3000 Gt C (1 Gt = 1,000,000,000 tons), versus 830 Gt C stored in the atmosphere (Figure 1). In terrestrial systems, the aboveground biomass holds 450–650 Gt C—about 80% of it in woodlands and forests.

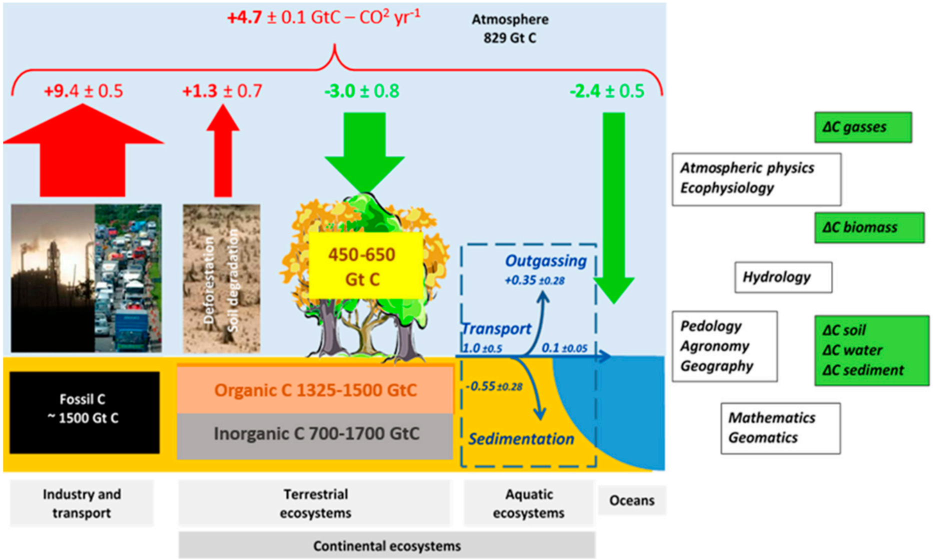

Figure 1. Estimation of natural and anthropic C and GHG stocks and fluxes between socio-ecosystems and the atmosphere, expressed as C-CO_2 equivalents. Time period covers last decades (2000–2010; 2007–2017). Fluxes shown are differences between inputs and outputs for each compartment at a global scale. Red fluxes correspond to anthropic emissions, adding to the natural C cycle (Green arrows: biosphere compartment excluding pedosphere, lithosphere and hydrosphere; blue arrows: water and sediments compartments). Estimated amounts (Gt C yr^{-1}) are supplied by [19,25]. Stocks of C in soil, plant, atmosphere and fossil pools are supplied respectively by [11] Soil C stocks are given for the soil surface layers (0–1 m). The C budgets (ΔC) are estimated on varying scales for compartments composing the Earth system (e.g., atmosphere; biomass, soil, and lakes.). White boxes on the right name the disciplines that describe, measure, model, and explained the C budgets.

2.1.2. C Pools within Soils, and Uncertainties

The uppermost meter of the world's soils, including peat, holds 1500–2400 Gt C, more than half of the total continental C stock. Forty percent of those stocks are held in forest and woodland soils [11]. Soil C stocks are highly heterogeneous because they depend (primarily) not only upon local vegetation, but also upon the type, mineralogy, and temporal evolution of local soils [26,27]. Carbon may be stored at depths as great as several meters, but quantifying deep-soil C stocks is a major challenge: the role of root biomass below 30 cm is still unclear, and empirical studies are needed in various environmental conditions.

An important (but controversial) quantity is the potential C sequestration/storage of a given land-use or type of agro-system. Said quantity is the maximum additional C that can possibly be sequestered/stored by switching to the given use or system from a reference one. The controversy arises, in part, from the difficulty of measuring C sequestration and C storage, as well as from the difficulties of characterizing not only the concepts themselves, but also the diverse biophysical processes involved. Both concepts are related to soil organic fluxes. The term "C sequestration" is used to refer to the process of "transferring CO_2 from the atmosphere into the soil" [28], and also to the result of that process within a given space and time (usually 20 years [29]): "the result of the net balance of all greenhouse gases, expressed in C-CO_2 equivalent or CO_2 equivalent, computing all emission sources at the soil-plant-atmosphere interface, and also all the indirect fluxes (gasoline, enteric emissions, etc.)" [15]. In contrast, "carbon storage" is defined as the increase in soil C stocks over time, "not necessarily associated with a net removal of CO_2 from the atmosphere" [28]. Like C sequestration, carbon storage is often defined for a specific land unit (surface and depth of soil). It is rarely calculated at the landscape level because a local C storage could be the result of C losses elsewhere.

Both terms refer to soil OM content and dynamics—i.e., to litter inputs, and to the decomposition and stabilization of OM through interaction with soil minerals [30]. If the potential is important to quantify, most importantly, additional C storage has to be measured in different contexts to make for sure or not that natural processes can offset the annual increase of CO_2 in the atmosphere. Few meta-analysis have shown that soil carbon sequestration is a solution for mitigating climate change over the next ten to twenty years [31,32]. Because soil C could be one of the greatest contributors to CoCS [22], addressing the scientific community's knowledge gaps about C sequestration and C storage as measurable biophysical processes is a key issue to the geoscience community (e.g., for evaluation) as well as to stakeholders (e.g., for developing legal tools).

2.1.3. C pools, fluxes within Aquatic Systems, and Uncertainties

In aquatic systems, organic and inorganic C stocks are variously held in sediments and dissolved or suspended in the water. The C stocks of inland aquatic systems remain poorly charted [33]. Carbon fluxes for aquatic systems are slightly better known, but are often estimated inaccurately due to insufficient measurements [34,35]. Estimates for aquatic systems (Figure 1) suggest that the C captured by terrestrial ecosystems is either released to the atmosphere, or else accumulates as sediment in rivers, lakes, estuaries, and coastal ecosystems [35]. The rate of aquatic outgassing (re-emission to the atmosphere) is estimated—with large uncertainties—at up to 3.9 Gt C yr^{-1} [34]. Human activities contributed 0.35 ± 0.28 GtC yr^{-1} to the increase in aquatic outgassing (Figure 1, [15,25]). However, data are needed to determine all the impacts of human activities in C cycle in aquatic systems. For instance, few studies quantify C content in sediments and compare input and output of sediments in and from dams' reservoirs. Recent results in Maghreb show that 55 to 72% of natural specific riverine suspended matter (SPM) are prevented to reach the sea since the 80s, [36]. Moreover, in recently setup dam's reservoirs, submersion of organic carbon contained in original soil and forests is followed by significant upstream and downstream emissions of CO2 and methane that may compensate for C fixation in sediments [37].

2.1.4. The Need to Improve Understanding and Measurement of C Pools, Stocks, and Fluxes

Terrestrial and aquatic fluxes must in principle be equal, but their calculated values disagree by about 0.6 Gt C yr^{-1} (See Table 6 in [19]). This substantial disagreement, which owes itself to a combination of underestimating emissions and overestimating continental or oceanic sinks, highlights the need to improve our measurement systems and our understanding of the C cycle [38].

At soil processes scale, while soil organic carbon fluxes are extensively studied depending on soil type, use and management. Soil inorganic carbon fluxes are often not measured, as soil inorganic carbon pool is considered static at least for short term studies (10–20 years). Yet, there are increasing evidences that equilibrium of the inorganic carbon pool may be shifted by external factors such as management practices and human-led environmental changes [39,40]. Studies on soil containing inorganic carbon, especially located in dry lands, should be promoted.

2.2. Targetable Knowledge: Reducing Uncertainties in Calculated C Stocks and CoCS Budgets

2.2.1. Create/Sustain Measurements Databases and Standardized Monitoring in Various Socio-Ecosystems to Monitor C Stocks and C Sequestration

To reduce uncertainties in calculation of C stocks and CoCS, we should continue to create and maintain databases of measurements from international and local one-off studies or monitoring campaigns. We should endeavor to harmonize and standardize data-acquisition methods to improve quality of the data and make them easier to use with existing book-keeping C models [39]. Methodological studies of measurements of C stocks and GHG fluxes are required to improve accuracy and acquisition speed, and to reduce costs [36,41]. Because CoCS encompasses a wide range of ecosystems, soil types, plants, and management practices, we will need many different types of measurements and, sometimes, specific measurement methods (not to mention safe access to fieldwork sites). CoCS comprises long-term processes; therefore, our efforts to monitor ecosystem changes and to improve data quality must be long-term as well.

2.2.2. Improve Modelling to Predict/Calculate C Stocks, Fluxes, Budgets, and their Climatic Feedbacks

Current models incorporate many biophysical processes at the global scale. (For example, links between C, water, and plant nutrient cycles; plus feedback between climate and CoCS budgets.) However, improvement is still possible [42], especially by articulating different C models built at different scales.

Such improvements will require scientists to address knowledge gaps and spatio-temporal uncertainties regarding biophysical processes. Notable examples of those gaps and uncertainties include:

- The poorly understood links between soil organic carbon and inorganic carbon pools.
- C transport between terrestrial and aquatic systems, particularly at the bottoms of slopes, along riverbanks, and in flood plains.
- Underground lateral C transport.
- Capture and release of C in the aquatic network.
- Terrestrial biological activities of soil and inland water macro-fauna and microorganisms, whose effects on CoCS budgets are poorly understood and may be controversial.
- The poorly understood links between rural and urban anthropic processes: e.g., OM transfers involving land uses and practices; the biophysical processes affected by OM transfers; and the effects of OM transfers upon CoCS [43].

The aims and the spatio-temporal scales of models should be stated clearly to reduce complexity and make the models easier to use by the scientific community and civil societies alike. To that end, researchers might improve global C models by classifying socio-environmental environments more precisely, and by defining each process clearly.

3. Processes Involved in the C cycle, from Individual Plants to Landscape Management

3.1. Diversity of Biophysical Processes and Human Processes; Upscaling to Landscape-Management Scenarios in CoCS

3.1.1. Biodiversity, land uses in the framework of C-allocation/CoCS

Carbon stocks in biomass and soils are affected strongly by land uses. Indeed, land-use changes—mainly deforestations—are the second-largest source of anthropogenic GHG emissions. Therefore, preserving C stocks in forests by avoiding deforestation and promoting afforestation is one of the main tools for enhancing CoCS [20].

Plants within landscapes are intrinsically linked by ecological or functional spaces such as plots, farms, and terroirs. As the plants interact with the environment (including anthropic interventions), they allocate C to the various ecosystem compartments (biosphere/rhizosphere, pedosphere, and lithosphere) in ways that vary according to plant species and local conditions. Therefore, complex agricultural landscapes with multifunctional land uses and mosaics of wild, spontaneous, and domesticated plants (hedgerows, copses, and bushes) favor CoCS by providing a range of ways in which vegetation can store and sequester C.

Limited land resources and land pressure for residential/institutional/commercial/industrial land uses could also lead to land cover changes from natural/semi-natural/agricultural areas to urban and industrial areas and then to a loss of ecosystem services and of carbon stocks [44,45]. Urbanization process compared to agricultural landscapes affect negatively the amount of C stored in artificial soils [46,47] but need to be quantified at various administrative scales.

3.1.2. Plant Diversity and Evolution of Landscapes According to Biophysical and Ideational Characteristics

Just as individual plants adapt themselves in response to changes in their biophysical environment, so do plant communities. The changes within that environment may derive from anthropic activities and socioeconomic conditions (e.g., climate change, loss of habitats, invasive species, and "ordinary biodiversity" within cities). Through complex processes, those changes play a major role in landscape evolution. A given region usually encloses several different, evolving, interacting landscapes [48]. As landscape biophysical characteristics change over time (i.e., its composition, configuration, functioning, history, and neighboring landscapes), so do their ideational characteristics—e.g., the perceptual filters and cultures of the landscape observers and inhabitants [49,50]. In response, those observers and inhabitants use the lands in ways that modify the plant communities' physical environment. Moreover, the stakeholders may differ considerably in their subjective cultural and ideational characteristics of landscapes. Therefore, landscape perception is an additional important factor to consider in detail when calculating C stocks.

3.1.3. Spatial and Temporal Variations of Landscapes; Modelling CoCS in Landscape Management Scenarios

Formalized modelling of spatial and temporal variations in landscapes is a valuable way to build new landscape-management scenarios. For modelling of CoCS, the scenarios would be "C-based". Of the various calculators that already exist for assessing landscape-scale GHG impacts of agricultural and forestry, the best-known are Climagri©, CoolFarm Tool, and Ex-ACT [51]. They calculate (more or less accurately) the C balance under different land-use and landscape-management scenarios (e.g., via storage in soils, formation of plant biomass, and influence of coastal waters [51]).

Temporal and geographical scales for management scenarios range from a single plant, with all its associated organisms, to combinations of plants ("plant assemblages"), then to functional-compartment organizations in the landscape, and thus to dynamics of changes in land-use and practices over time [51]. Such dynamics—key issues in CoCS modelling—involve human factors. The landscape-management decisions that affect agricultural productivity are often based upon human perception and landscape ideational characteristics. Therefore, leading-edge interdisciplinary research on CoCS and related indicators seeks to formalize all biophysical, agricultural, socioeconomic, physical, and ideational characteristics of landscapes.

3.2. Targetable Knowledge: Identifying Processes on Which Innovative Technique Can Be Based

3.2.1. At the Plant Level: Specify and Quantify Factors Limiting Photosynthesis and C Metabolites Remaining in the Soil

At the scale of individual plants, research priorities are:

- Identify interactions between rhizosphere microbiota and the C, water, and plant-nutrient cycles (e.g., N, P, and K).
- Quantify fraction of net primary production and C metabolites remaining in the soil.
- Study the factors that limit photosynthesis, and the plants species that circumvent these limits.

The knowledge gained will enable the development of effective, long-term, innovative techniques to increase root growth, root-associated beneficial microbiota, and mycorrhizal or actinorhizal symbiosis. More generally, that knowledge will help to increase efficiency of photosynthesis, nutrient and water uptake and utilization, and consequently the transfer of atmospheric C into plant biomass, and then into soils. Characterization and functional analysis of the rhizosphere microbiome will also reveal how its role in GHG emissions (CO_2, N_2O, and CH_4) depends upon soil type, water conditions, plant communities, and the insertion of these communities at the landscape scale.

3.2.2. Between Plants and Landscape Levels: Developing Methods to Foster Monitoring of Innovative Plant Management for CoCS

New plant selections for enhanced CoCS may come from species ignored by plant breeding institutes focusing on plant varieties that potentially allocate more C to harvestable organs (i.e., are more productive) than to residues (e.g., increasing soil efficiencies). Hence, selection of plants for CoCS has to be reoriented towards species whose physiology provides a satisfactory compromise between C allocation to (1) the grain and aboveground residues (stalks), and (2) the belowground rhizo-deposition (roots and roots exudation). For landscape-scale studies, researchers must develop low-cost, high-speed phenotyping methods, as well as robust methods for identifying physiological traits associated with C capturing, plus its allocating to roots and underground storage organs. For example, infrared spectrometry might be used to characterize spatio-temporal dynamics of CoCS on scales from plants/plots (using spectroradiometers or spectrophotometers) to landscapes/regions (via satellite images and remote sensing). The results would feed databases on C in biomass and soils [41,52].

3.2.3. At the Landscape Level: Specify Links Between Biodiversity and CoCS

At the level of the plant community, researchers have seldom studied how plant associations and forest biodiversity affect CoCS. Landscape-level studies (e.g., on woodlands and forests) are even scarcer. Recent innovations are based upon plant biodiversity, among other things: for example, cover crops, multilayer cropping, agroforestry, and agro-ecology. Agroforestry practices and systems are known to enhance C storage in the biomass and soils [53]. Little is known about deep-soil C dynamics and factors controlling deep-soil C stocks (root turnover and soil OM). However, these subjects have received increasing attention in recent years [54] because they promise to identify ways to enhance C storage [55].

3.2.4. How CoCS is Affected by Agricultural Practices and by Scales of Land-Use Management Under Different Intensities of Land Use

Soil microbiota and macro-fauna enhance CoCS by mineralizing and stabilizing soil C stocks. The activity of these organisms is affected by all practices for increasing OM applications and biomass production (e.g., by mulching, compost, manure, and water conservation), as well as by the selection of plants and plant associations. Because these practices are common in agro-ecology, research continues on how they affect ecosystem functions—including their quantitative effects upon CoCS.

Innovations for increasing CoCS must be based mainly upon an understanding of processes that control C stocks and fluxes at different geographical scales, and for a range of land-use intensities (e.g., natural, agricultural, peri-urban, and urban). Therefore, we also need a better understanding of the functional ecology of different types of agricultural systems in relation to various bioclimatic conditions, to landscape diversity that composes them, and to soil biodiversity and microbial communities as affected by agricultural practices.

3.2.5. Facilitating Shifts from Plant-Scale to Landscape-Scale Management and CoCS Modelling

CoCS is affected by a range of processes, on scales ranging from the microscopic to vast biogeographical areas. The biophysical processes that stabilize C operate at very fine scales: from the individual plant that traps CO_2, to particles of clay that stabilize C, to microorganisms, those contributing to form stable C through polymerization, or those mineralizing OM, which, otherwise, would emit GHGs. In contrast, environmental and socioeconomic processes act at regional scales. Therefore, scaling is indispensable to a better understanding of biophysical processes of CoCS [27], and also for socioeconomic issues.

Diverse methods exist for upscaling local C-stock measurements and studies of C processes to larger areas. The methods include empirical ones (describing and explaining the variability of the locally measured quantity) and those based upon modelling of processes (e.g., simulating water and C fluxes at the scale of one entity within an agro-system [56]). Such approaches can be used conjointly, particularly for characterizing model uncertainties when upscaling. Upscaling asks for integrating various C compartments and landscape features (forest, agricultural, urban areas) with their own characteristics, dynamics and uncertainties. Furthermore, upscaling is not simply juxtaposition of compartments, as all of them interact. Yet, this difficult exercise of upscaling is urgently needed to foster policy supports for CoCS.

3.2.6. Toward a Typology for Classifying Soil and Plant Processes

Upscaling of C measurements and processes can be facilitated by classifying the processes that occur within soil/plant systems. To that end, scientists formulate soilscapes (maps of soil-type distributions within a landscape [57]. Within one soilscape layout, scientists are able to estimate lateral C transport between compartments (Figure 2), and in general this makes possible a better understanding of how CoCS depends upon soils, complexity of the vegetation cover, and abiotic factors (e.g., atmosphere and hydrosphere). Upscaling to continental and global levels remains a challenge, and will display large uncertainties, but is the only way to evaluate the effect of CoCS upon global warming.

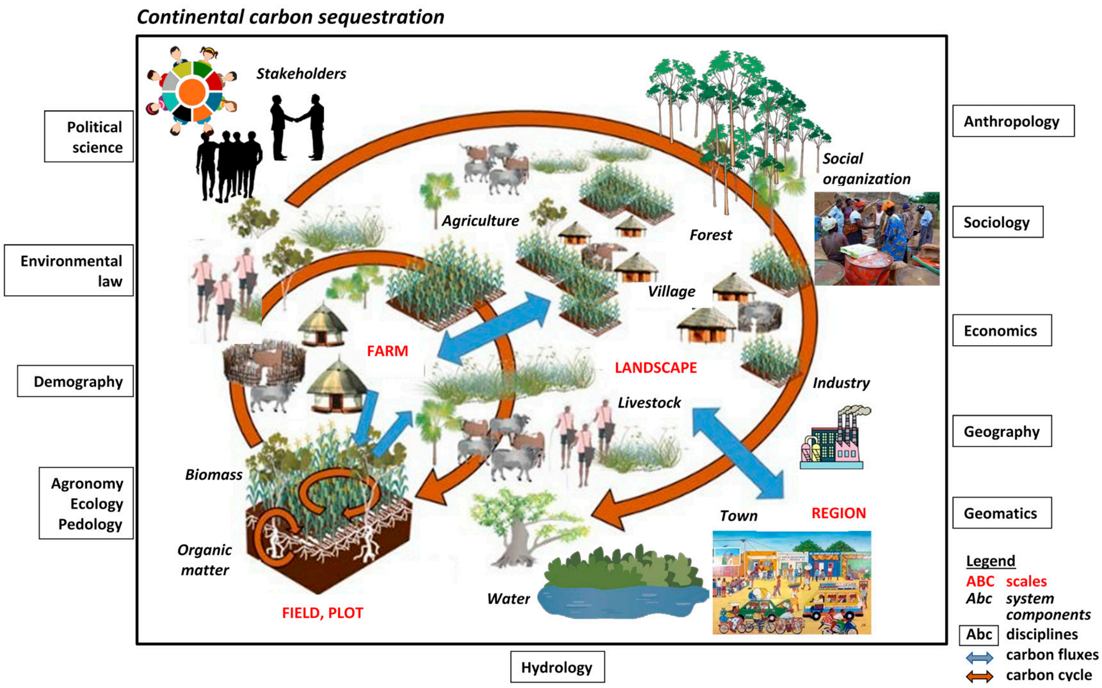

Figure 2. Graphic displaying CoCS complexity and interdisciplinary questionings. The understanding of processes leading to C (de)sequestration and C transfers between compartments must take into account various spatio-temporal scales and stakeholders. Therefore, many scientific fields are involved in questioning such processes, both uni- and pluri-laterally.

4. Viability, Vulnerability, and Resilience in CoCS Practices

4.1. Participative Research as a Holistic Approach in CoCS

Multi-disciplinary analysis, with a holistic approach, appears to promise innovations that will provide multiple useful functions. Innovations to increase CoCS at the landscape scale must take into account the diversity of local biophysical and socio-economic environments therein, as well as all the inhabitants' current uses and practices, whether or not they are involved in C sequestration. A number of alternatives must also be proposed for different types of landscapes [58]. The CoCS potential for different land uses must be evaluated in coordination with a variety of stakeholders who are involved, such as extension services, private sector, civil society, local institutions, policy makers, and consumers—not just farmers [59].

As an example of why stakeholders of many types must be consulted, consider the effects of trees in a landscape. The presence of trees changes agricultural work when the trees are within fields, as in agroforestry, or in hedges or thickets between fields. However, the trees also change the landscape, the perception of agriculture, and land-management policies. Participative research and joint projects foster the involvement of diverse stakeholders, and should therefore be central to the search for ways to increase CoCS at landscape or regional scales. Hence, it is unfortunate that participative research and joint projects have seen little use in initiatives for developing or deploying CoCS innovations such as intercropping, agroforestry, integrated crop-livestock farming systems, urban compost, and use of wastewater in suburban/peri-urban agriculture. Local adaptation is a sine qua non for sustainable application of these innovations, and thus for identification of generic and specific CoCS processes in diverse socio-ecosystems.

4.2. Sustainable Development and the Juridical Challenges of CoCS Implementation

Political pledges for "zero hunger" and "climate action" SDGs can synergize with each other and with enhancement of CoCS. For example, C storage can reduce land degradation and soil erosion. However, the two types of pledges can also appear to conflict with each other because food-production benefits from soil OM decay (e.g., biological activity and associated nutrient release for plant growth), while climate action benefits from OM stabilization, i.e., not only that OM be maintained, but also for example that forests expand at the expense of agriculture [60,61]. SDG pledges take effect through various mechanisms: international laws and agreements, and national and local policies, laws, regulations, and actions. To enhance CoCS, those mechanisms must endorse agricultural practices and infrastructures that will restore or promote natural C sinks without affecting, or even promoting food security. Various points of view should be considered when formulating those mechanisms, from the most abstract (systems theory) to the most practical (agricultural transformation and associated practices). Bottom-up and top-down governance must both be considered to develop practices for increasing C stocks while reducing the vulnerability of socio-ecosystems and increasing their resilience.

4.3. A Long-Term Timescale to Better Understand CoCS Dynamics and Their Juridical Implementation within Socio-Ecosystems

Biophysical processes of sequestration and stabilization in ecosystems are detectable and measurable only over relatively long timescales (at least 10 years). Therefore, research into CoCS must establish definitions and evaluation criteria for Good Management Practices *a priori*, based upon how likely such practices be adopted on the long run, as well as on their benefits and costs. Because the global-warming consequences of CoCS are not "tangible" issues for populations, we will face challenges when instituting long-term juridical and local practices that foster CoCS in ways that will allow the whole population to share the benefits.

4.4. Side Benefits of CoCS Juridical Implementation for Socio Ecosystems, from Local to Global

The many possible side benefits of practices that increase C stocks may, by themselves, justify adoption of such practices [22,62]. Those benefits include greater fertility of poor soils, restoration/rehabilitation of degraded land, less run-off and erosion of fragile soils, increased water reserves, and richer biodiversity. Although these side benefits are often asserted a priori, they are still poorly quantified or even ignored in many socio-environmental situations. Therefore, they must be evaluated for each situation, and characterized and quantified at various spatial and temporal scales. The evaluations must distinguish between local/individual aims (soil fertility, yields) and global/collective ones (limiting global warming, maintaining biodiversity, food security) while also taking societal, economic, and ecological viewpoints into account. Policies for encouraging the adoption of practices to increase C stocks must include criteria other than those directly related to C budgets.

For example, nutrient and water budgets, albedo, pollution, food production, labor costs, farm revenue, and perceived or real financial and ecological risks. When stating their primary objectives, studies must distinguish between generic/global benefits and specific/local benefits; i.e., to determine which benefits, or recommendations, associated with a specific practice to increase C stocks could be valid anywhere, at any time.

4.5. Targetable Knowledge: Understanding the Process of Adopting Practices to Increase C Stocks

4.5.1. Engage Stakeholders in Participative Research to Implement CoCS Practices

To ensure quick adoption of practices for increasing C stocks, a diversity of stakeholders must be engaged. To make that adoption permanent, information must be acquired and disseminated, including via production and publication of scientific knowledge as part of public or private actions. Reducing the time needed between steps and for each step would benefit any given adoption initiative, as well as the CoCS-enhancement initiative as a whole. Co-construction of knowledge, with a participative-research approach would help by bringing together stakeholders, scientists, and decision-makers at each stage and for each locality. Although this approach might appear simple, its application is a very active research topic. In France, C sinks receive attention in the local climate, air, energy, and territory (PCAET) plans established by the Environment and Energy Management Agency (ADEME) [63]. A study of the methods used to formulate and implement those plans might provide useful insights into principles for aggregating various contributions to C storage.

4.5.2. Identified Issues in Participative Research on CoCS and the Implementation of CoCS Practices

When participating in a CoCS-related initiative, scientists must often provide knowledge that they do not yet possess—for example, factors controlling CoCS, simple and cheap/convenient methods and indicators for CoCS, and side effects of the recommended practices. Therefore, participative research must address several issues when characterizing each option and strategy in order to foster CoCS adoption:

- Identifying routes, speeds, obstructions, stocks, transformations, points of no return, and real or perceived risks taken by individuals, families, and local government when adopting or continuing practices to increase C stocks.
- Identifying social, cultural, and financial constraints: What are the characteristics of the local community that may influence individual or collective adoption of particular practices? (e.g., what are the inhabitants' needs; cultural, social, and agricultural customs, standards of living, and financial resources?) Also, how do the inhabitants' relationships with administrative, legislative, and political systems affect their agricultural choices?

Answers to such questions would show the level of integration of CoCS into the local government's objectives and plans. The answers would also reveal relationships between practices/options to increase C stocks, and the social scales at which decisions are made and implemented (family, lineage, village, town, etc.). Implementation of practices to increase C stocks must take into account the allocation of benefits and ensure equality among different social groups—for example, among professions and between genders. Therefore, research is needed to develop methods for identifying, measuring, and tracking such post-implementation social consequences at various spatial and temporal scales [64].

4.6. Targetable Knowledge: Improving Viability of Practices to Increase C Stocks, from Land Tenure and Agricultural Stakeholders to Consumers

Carbon sinks are dynamic: after storage, C may be lost again through inappropriate land uses or practices. Therefore, viability of practices maintaining CoCS must be improved. Those practices depend upon:

- Individual and collective benefits from C stocks, and

- Support from appropriate social, financial, legal, and technological tools.

Evaluation of these practices must engage disciplines beyond those involved in biophysical or economic modelling. For example, the models used for evaluations could incorporate viability theory [65]. Land tenure is another important issue for CoCS research because CoCS areas and potentials are directly affected by the laws through which society secures natural and agricultural land tenure, and governs urban development and infrastructure. For producers, agricultural practices will be attractive with reasonable labor costs and sustainable distribution channels (transporters, processors, and markets). Viability analysis of practices to increase C stocks might thus include the whole sector, from production to distribution, considering pros and cons for every actor: producers, sellers and consumers.

That analysis may be trans-regional, and treat multiple spatio-temporal scales. Local governments require coherent public policies to ensure long-term viability of practices that increase C stocks. Unfortunately, public policies have often (for socioeconomic reasons) supported "key" agricultural products such as milk, cereals, palm oil, and latex. The resulting regional specialization and simplification of cultural systems has decreased the use of plant rotations and other CoCS-enhancing practices. Public-funded research has exacerbated this trend by concentrating on the improvement of "ideal plants". Such contradictions between policies must be better understood, formalized, and evaluated to tackle these issues. Our understanding of the role of CoCS practices within socio-ecosystems would be improved by better knowledge on the links between CoCS and socio-environmental challenges such as biodiversity, public health, and social equality.

5. Moving toward Sustainability Science

5.1. The Paris Agreement and Nationally Determined Contributions (NDCs): Mismatch between Calculated and Recommended CoCS Budgets

Countries that have committed to NDCs under the Paris Agreement aim at "achieving a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases" [66]. However, detailed CoCS budgets are rarely drawn up and included in NDCs. The countries' reasons for omitting their budgets (if they exist) are rarely analyzed. One possibility is that the budgets are too imprecise for policy-making because of uncertainties in the budgets themselves, or because of excessive spatio-temporal variability. In addition, scientific results are probably not sufficiently shared with non-academic audiences. This disconnection can limit use of CoCS budgets by governments and administrations. Gaps such as those noted above present opportunities for disciplinary and multidisciplinary collaborations with stakeholders/decision-makers to design Human-Environment monitoring centres [observatories], focused on CoCS.

The AFOLU sector plays a major role in strategies for reducing and sequestering CO_2 [21]. The Koronivia Joint Work on Agriculture enabled the agricultural sector to enter progressively into climate negotiations [67]. Similarly, the vast majority (89%) of the NDCs, especially in the developing countries, propose actions in the AFOLU sector to mitigate climate change and adapt to it. In contrast, few countries specify the concrete, quantified actions that they envision for reducing GHGs or enhancing CoCS [68]. For this reason, the Green Climate Fund does not finance AFOLU projects sufficiently: 27% of the projects financed by the Fund are for AFOLU, but receive only 10% of the Fund's budget [69]. In addition to the Climate budgets, the Land Degradation Neutrality (LDN) funds of the Convention to Combat Desertification (UNCCD) are entirely dedicated to the AFOLU sector.

5.2. From Biophysical Processes of CoCS to the Inclusion of Human Sciences: Defragmenting the Field of CoCS

As we have seen, CoCS (and more directly; C-storage potential) depend strongly upon multifactorial biophysical, technical, and socio-economic variables [70]. The biophysical processes involved in CoCS act over a wide range of scales, and are studied by scientists from numerous disciplines: eco-physiologists, pedologists, ecologists, microbiologists, hydrologists, biophysicists, biogeochemists, etc. However, many recommendations in scientific literature on CoCS [22,71] are drawn from large-scale spatial studies [72] and meta-analyses [23,31,73,74], few of which are comprehensive studies that include all the biophysical processes within a region [75]. Interactions between those processes and land management tend to be studied by scientists who are rarely concerned with CoCS. For example, by agronomists, geographers, economists, anthropologists, jurists, and specialists in international cooperation and politics [76,77]. Therefore, knowledge on CoCS remains fragmented, sometimes leading to unclear recommendations.

5.3. Organizing Existing Knowledge

5.3.1. Achieving Homogeneity of CoCS Concepts and Databases for Transdisciplinary Objectives

A CoCS thesaurus, data infrastructures, and information system would enhance the sharing of knowledge needed to design, build, and use models based on the heterogeneous data and know-how of several disciplines. Observatories and long-term socioeconomic research platforms may further this approach by attaching research to the land and providing a channel between scientists, stakeholders, and decision-makers [78,79]. However, we need to ensure that the data thereby produced does not remain dispersed, too general, tied to particular activities, or incomplete. As a preventive measure, and to build a common basis for further thought, existing knowledge might be organized according to concepts, using terms that are agreed-upon among various disciplines and activities.

5.3.2. Having Strong Policy Support for CoCS Systems (from Fundamental Research to Implementation)

Deficient communication of scientific knowledge and recommendations to decision-makers [80,81] hinders the formulation, understanding, and implementation of policies [82]. Therefore, we need a new model for field measurements, monitoring, and demonstration so that we may understand, monitor, and disclose causes, mechanisms, and consequences of CoCS. That model should organize the production of hybrid knowledge based on individual and collective strategies for local-development [83].

5.3.3. Building Man-Environment Observatories as a Framework for Moving Toward a CoCS Sustainability Science

Implementing an observatory model in one or more regions will formalize the communication about newly gained knowledge, and facilitate its use by decision-makers [79]. A combination of CoCS observatories and an interdisciplinary scientific community to study CoCS could lead to the construction of an ontology ("An ontology defines the basic terms and relations comprising the vocabulary of a topic area as well as the rules for combining terms and relations to define extensions to the vocabulary" [84]) for the domain. This new scientific community should build a strategy for interdisciplinary communication, with loud and convincing messages. Media use should be appropriate to each audience: scientific papers and books for academics and non-academics, policy briefings for local and national decision-makers, and experimental sites for demonstrating principles. The latter medium could have a great effect upon politicians and the general public.

5.4. Produce Hybrid Knowledge (Building Bridges between the Scientific Community, General Public, and Decision-Makers)

5.4.1. Fostering Communication among Stakeholders (Scientists, Producers, Decision-Makers, and Citizens)

Scientists, citizens, civil society organizations, decision makers, extension services, and farmers may cross paths, but they do not necessarily act in concert with the same environmental, geographical, or societal objectives in a given region. All stakeholders transform their region through their reflections, decisions, work, and practices; they contribute to regional, legal or symbolic, appropriation by social groups [85], and describe their region by using their own cultural signs or codes [86]. Bridges must be built among stakeholders to coordinate action plans and ensure that the solutions are permanent. If scientific research is to contribute to the management of a region, the results of that research must be explained clearly—especially the pertinence and limitations of the models used.

Political initiatives, such as 4 per 1000, can foster communication between politicians and stakeholders. However, the success of such initiatives depends upon the level of interaction and communication. By soliciting input from a variety of regional agents during the modelling processes, researchers may increase the chances that stakeholders will understand and use the results. At different moments of the process, it may prove helpful to collecting and sharing information and points of view may help, via dialogs using the "landscape", as understood and perceived by the diversity of stakeholders [87]. The methods employed in collaborative research with scientists and stakeholders are a whole research domain in itself. For example, how to reach an agreement about objectives, spatial area, time scale? and what are the parameters to consider? That process should identify scenarios and highlight not just obstacles, but also points of leverage and favorable areas for CoCS. Collaborative research should encourage the various stakeholders to think in terms of bundles of local services that are separate from global services, and to think in terms of side benefits, and ecological costs and impacts, inside but also outside the region [64].

5.4.2. Broad Spatio-Temporal Scales: International and Local Agreements with Inclusion of CoCS in Development Plans and Guides

For long-term policies at national scales, formalized knowledge and simulations may be used to draw up the national action plans required under international conventions—that is, NDCs to slow climate change, and LDN targets to mitigate land degradation. At local scales, and on shorter timescales, formalized knowledge and simulations will help local stakeholders to include CoCS in their development plans, and to agree on local regulations that will encourage good practices and guide local policies [88,89]. To ensure that CoCS policies are equitable, administrative units and their stakeholders must recognize and carry out their respective roles during different stages and for different C pools.

6. Conclusions

Strengthening continental ecosystem management and conservation, i.e., agriculture and forestry sector, to enhance negative GHG emissions should be encouraged. Solutions need to mobilize various scientific and traditional knowledge and are not unique, "one size fits all" being not applicable. Such solutions, adapted to various geographical and socio-ecological scales, engage numerous stakeholders, from consumers, farmers, to international cooperation. That said, scientific uncertainties on CoCS budgets restrain the implementation of sustainable land management practices, suitable for the considered scale and context. Some studies monitoring benefits for climate mitigation and adaptation, food production and land degradation restoration existed, but they scarcely tackled all these issues in the same time for a given land space.

Organizing and formalizing available knowledge—e.g., concepts, data, policy supports—simulate development plan for all the stakeholders, and define local, equitable and viable policies where respective roles of all stakeholders are specified. Such organization and formalization are essential to reinforce the credibility of such alternatives. We advocate for a pluri-disciplinary approach, including the implementation of Man-Environment observatories. These are efficient opportunities to gather interdisciplinary scientific community, key stakeholders of the civil society—e.g., farmers, extension services—as well as policy makers working at different levels (territories and issues associated to CoCS). Observatories on CoCS will contribute to generate and unbind knowledge. Moreover, data and models jointly collected and produced from these multi-stakeholders' observatories are means to nurture international initiatives: 4 per 1000, Land Degradation, Koronivia Joint Work on agriculture, the fulfilment of National Determined Contribution and finally national engagements approved during the Paris Agreement.

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